



# Alkali Metal Heat Pipes for Space Fission Power

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# Outline

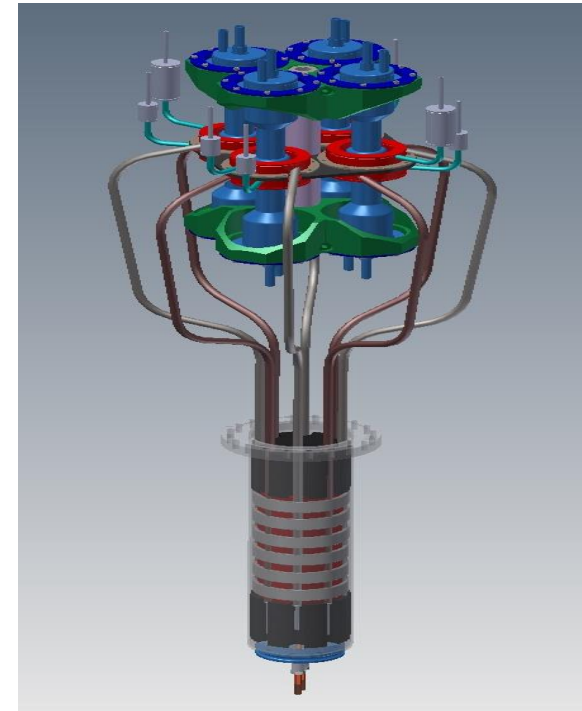
- Motivation
- Background – Self-Venting Arterial Heat Pipes
- Objectives
- Self-Venting Arterial Heat Pipe Fabrication and Testing
  - 1/2" Self-venting arterial heat pipe development
    - Radius Bend Heat Pipe With Venting Pores Development
- Thermosyphon Fabrication and Testing
- VCHP Feature
- Condenser Development
- Future Work
- Acknowledgements





# Motivation

- NASA Glenn is examining small fission reactors for future space transportation and surface power applications
  - The reactors would have an 8 to 15 year design life that could be available for a 2020 launch to support future NASA science missions
  - 1 kWe Stirling system.
- Alkali metal heat pipes would be used to transfer heat from the reactor to the Stirling water heat pipes to transfer the waste heat from the Stirling engines to a radiator panel





# Background

## ❑ Constant Conductance Heat Pipes (CCHPs) grooved heat pipes

- Standard wick used in spacecraft CCHPs, diodes, and Variable Conductance Heat Pipes (VCHPs)
- Benefit of the grooved wick is that it cannot be de-primed by vapor bubbles since the bubbles can vent into the vapor space.
- Grooves have a very high permeability, allowing very long heat pipes for operation in zero-g.
- Only flaw is that they are suitable only for space or for gravity aided sections of a heat pipe
  - Same large pore size responsible for the high permeability results in low pumping capability.

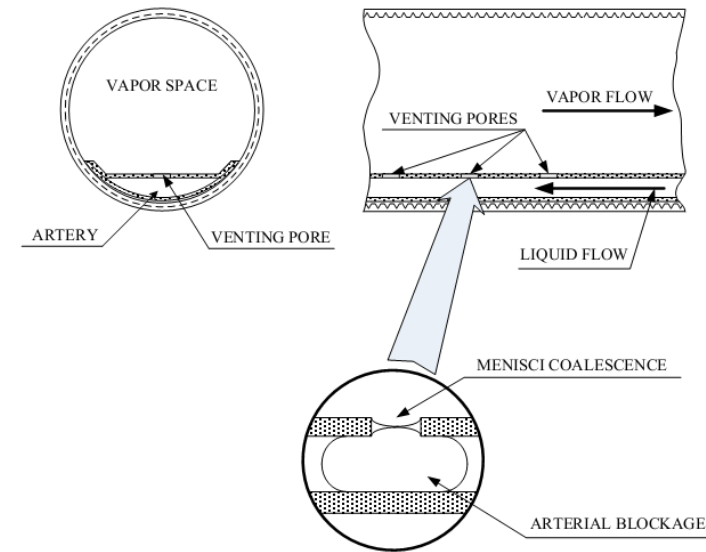




# Background

## ❑ Constant Conductance Heat Pipes (CCHPs) Self-Venting Arterial Heat Pipes

- Artery in this variation of CCHP is created using a screen wick at the base of the heat pipe that creates a single artery for the liquid return flow.
- Benefit of a wick with high wick permeability and small pore size and thus a high capillary limit.
- Difference from a conventional arterial pipe is that small venting pores are located in the evaporator section of the CCHP:
  - The venting pores provide an escape route for any trapped vapor or NCG in the artery.
  - The design eliminates the single point failure nature of previous arterial CCHPs.



Kaya et. al, 2011



# Concept of Self-Venting Arterial CCHP

- The use of vapor vent holes in an arterial CCHP wick was first introduced by Eninger in 1974.
- Diameter needs to be calculated so that if a blockage occurs, the menisci formed on both sides of the venting hole can coalesce to allow priming of the artery.
- Same venting hole technique was used in arterial heat pipes of the thermal cooling system of Communication Technology Satellite (CTS) (Mock et al., 1975).
- The self-priming heat pipe design has been validated with ammonia in numerous Russian spacecraft (TRL 9).





# Background

- Arterial heat pipes are the current default design for spacecraft nuclear reactors, however, de-priming of the artery due to radiation in a nuclear reactor is a serious potential problem.
- Grooved and self-venting arterial heat pipes offer potential benefits over standard arterial heat pipes
  - The grooves cannot be de-primed
  - The self-venting arterial pipes are less susceptible to de-priming and have a lower mass.
- Alkali metal heat pipes with these wicks have never been tested
- Initial testing showed that self-venting arterial heat pipes performed better than the grooved heat pipes – down selected for the Phase II.





# Technical Objectives

- **Overall Objective:** Develop low-mass alkali metal heat pipes for space fission reactors, examining the trade-offs between grooved, conventional arterial and self-venting arterial heat pipe wicks
  - Fabricate and test full length versions of the self-venting arterial wick heat pipes for the Stirling energy conversion systems.
  - Develop suitable heat pipes for the Kilopower system:
    - 9 pipes – 3 fully wicked and the rest of them wicked only in the evaporator
    - Investigate the suitability of using self-venting arterial wick structure in gravity aided orientation
  - Develop angled/bent self-venting heat pipes



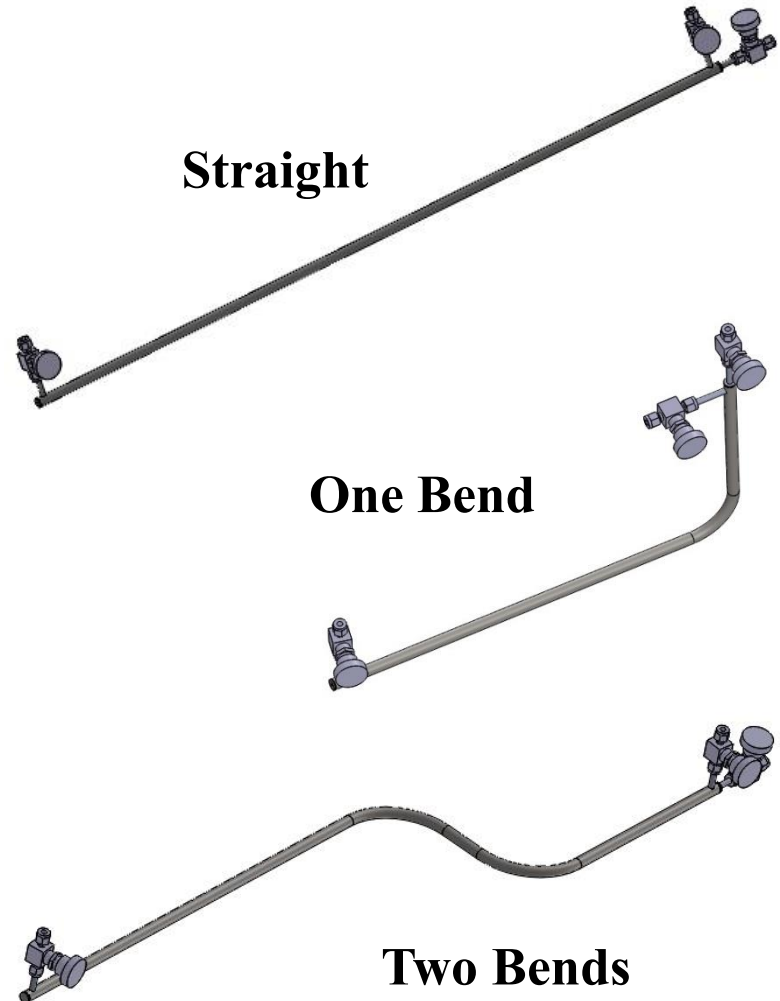




# Development Toward the Full Scale Configuration

- **Bend development**

- To evaluate if artery heat pipes can be manufactured in bent configurations
- 39.37 inch overall length, 3.0" radius 90° bends
- 6 inch evaporator section, 6 inch condenser section
- Bend 1 is 12" overall length from condenser end
- Bend 2 is 2" (end of first bend to start of second bend) toward the evaporator. This simulates the two closest bends in the deliverable heat pipes.
- .094" square artery. 0.30" venting pores diameter and 0.80" spacing in the evaporator artery
- Radius bend heat pipe to be manufactured and performance tested straight, then bent. Will have venting pores
  - 0.50 inch OD x .035 inch wall stainless steel 316 shell
  - 250/inch mesh x .0016 wire diameter stainless steel 316 screen wick
- All testing in vacuum chamber



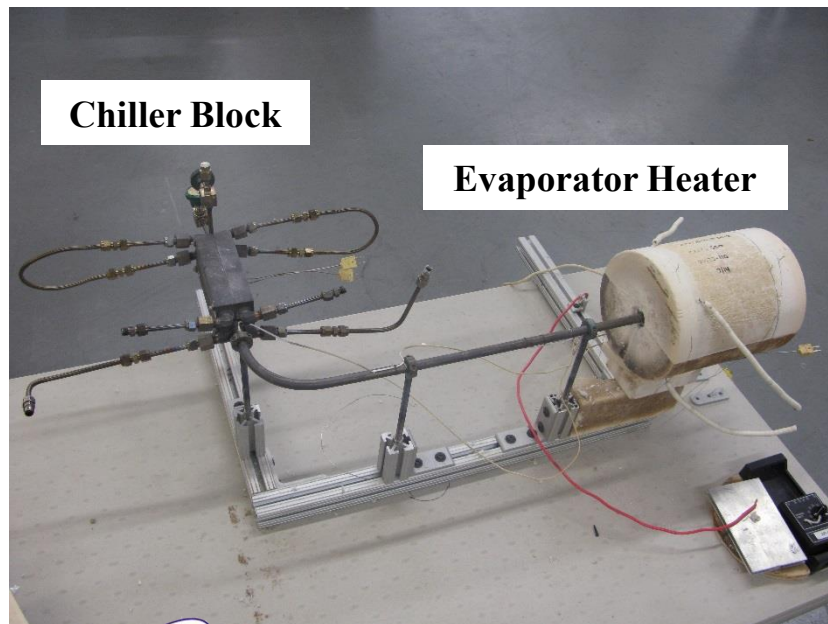


# Radius Bend Artery Heat Pipe

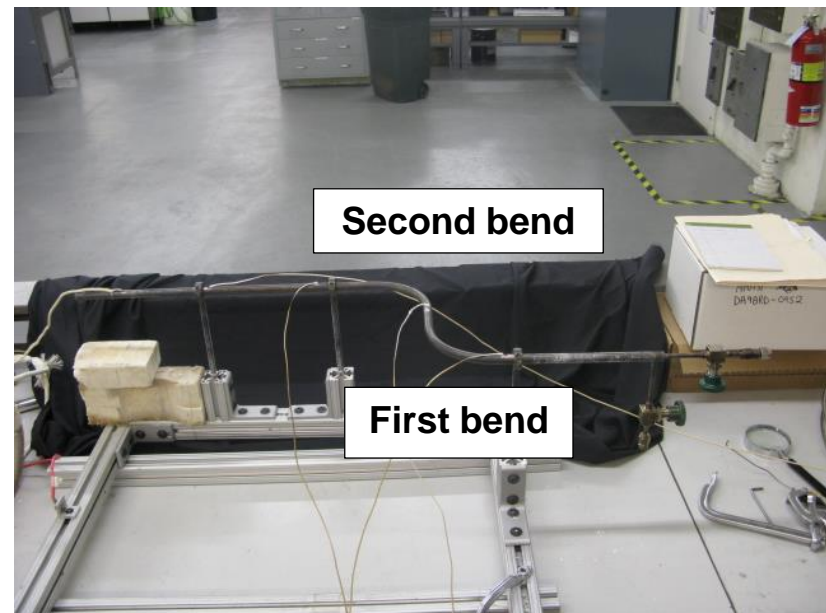
## Straight



## One Bend



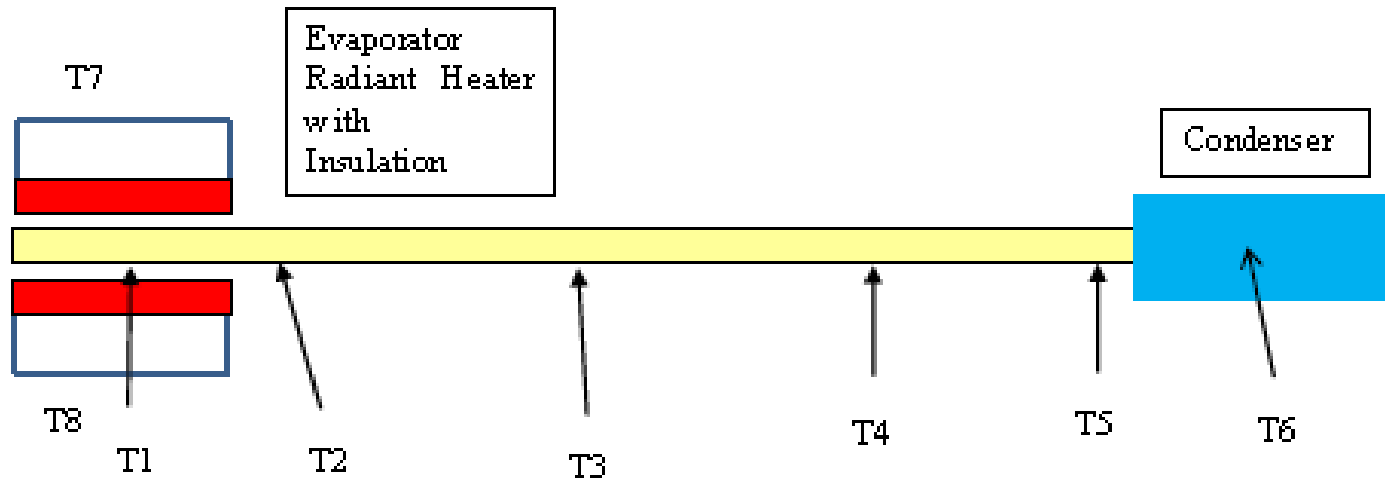
## Two Bends





# Radius Bend Heat Pipe Thermocouple Locations

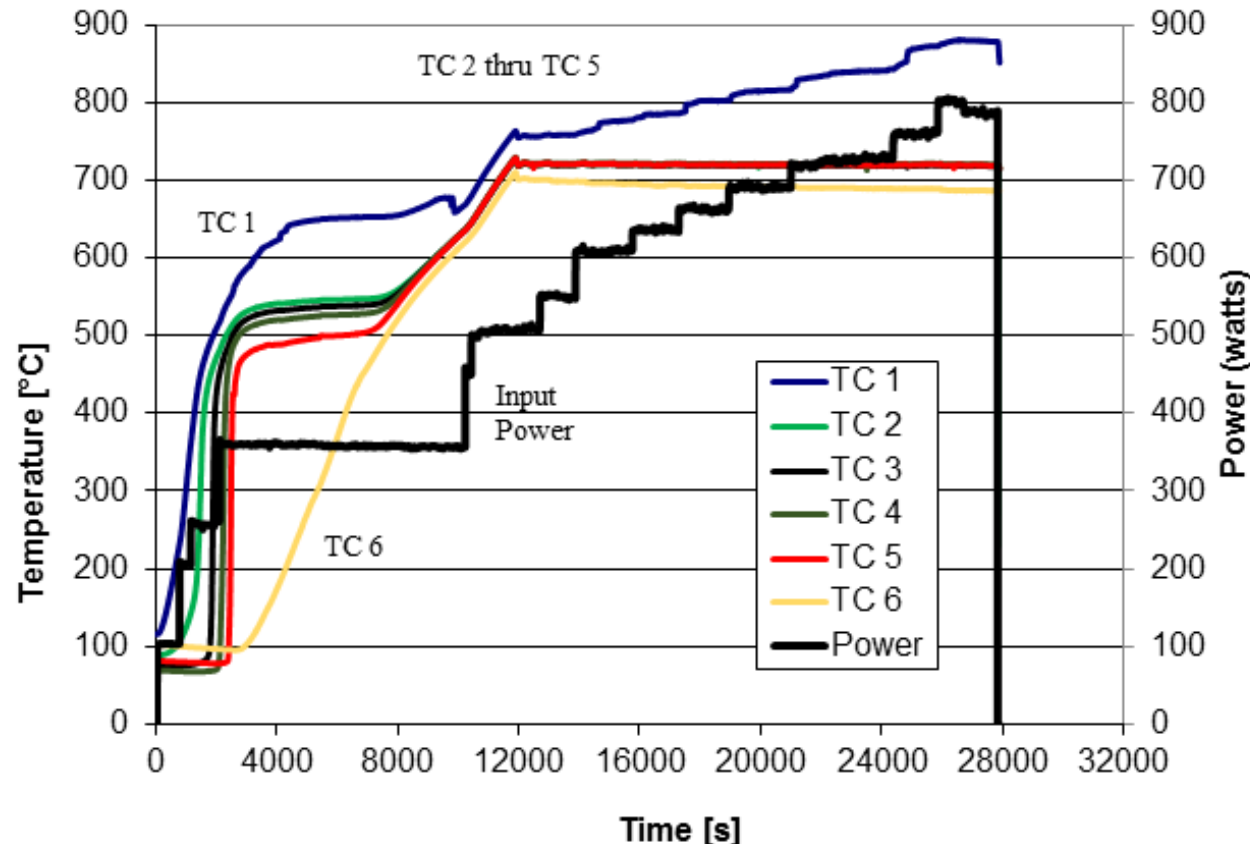
- ◆ Location and numbering Of thermocouples.
- ◆ T1 thru T5 are on the heat pipe surface
- ◆ T6 is in the condenser chill block
- ◆ T7 and T8 monitors the temperature of the heater insulation. This is to determine the effect of heater radiation heat loss in relation to thermosyphon operating temperature





## Straight Configuration (Before Bending)

- ◆ Elevation of 0.3" against gravity was introduced to avoid puddle flow.
- ◆ The final power input into the system was 780W yielding a transport power of 520W when the heat losses (260 watts) are subtracted.



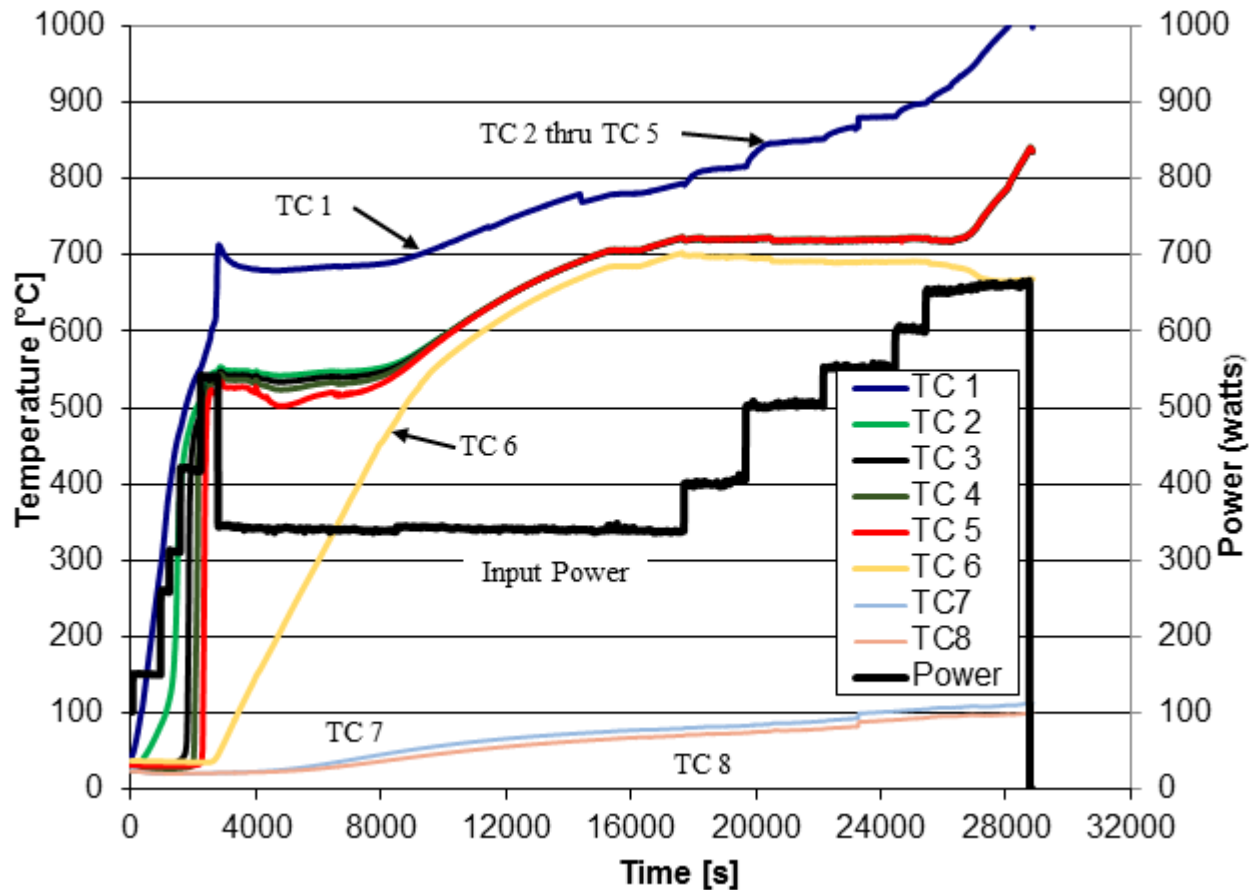
Horizontal (0.3" adverse) testing of 1m straight arterial heat pipe in vacuum chamber





## Straight Configuration (Before Bending)

- ◆ Elevation of 1" against gravity.
- ◆ The final power input into the system was 600W yielding a transport power of 340W when the heat losses (260 watts) are subtracted.



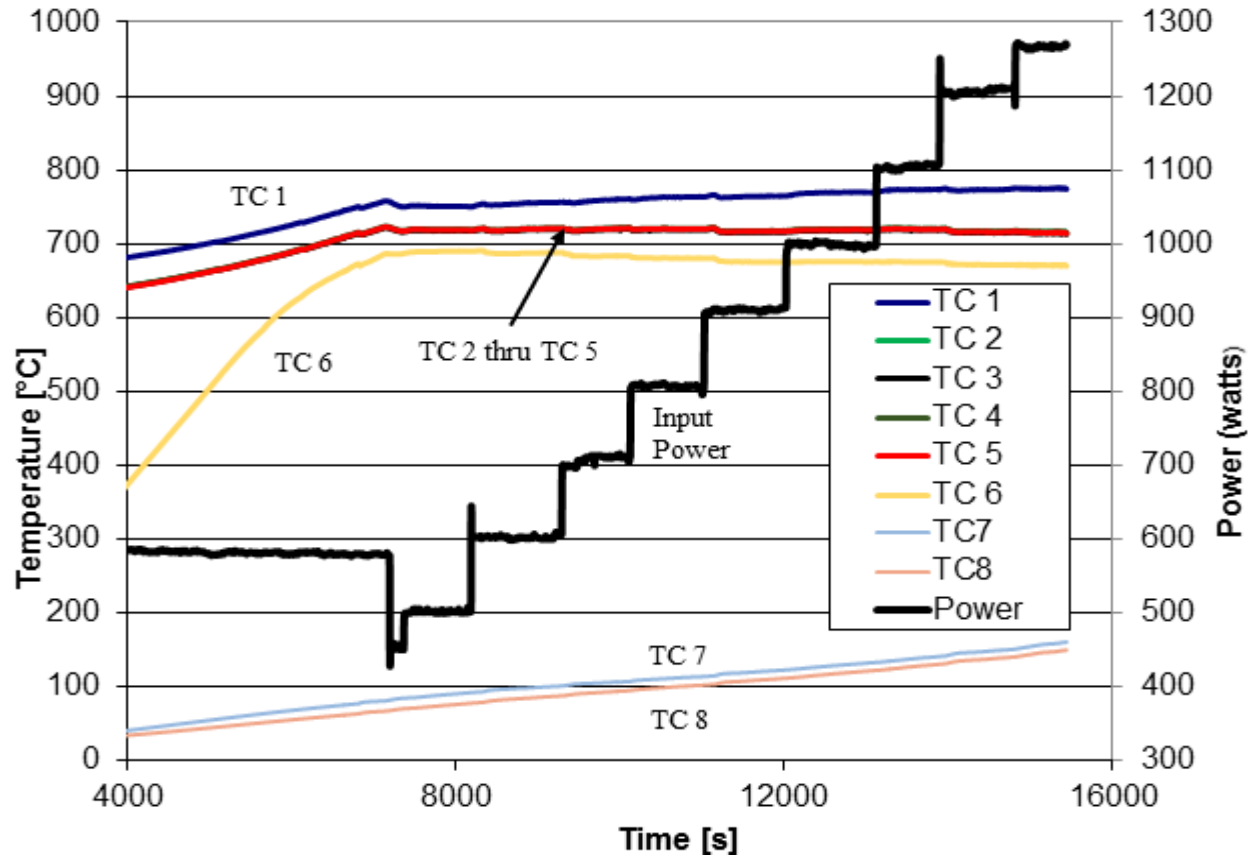
**1" Adverse testing of straight arterial heat pipe in vacuum chamber**





## Straight Configuration (Before Bending)

- ◆ Thermosyphon operation, heat pipe at 45° (*restrictions imposed by the vacuum chamber size*).
- ◆ The final power input into the system was 1260W yielding a transport power of 1000W when the heat losses (260 watts) are subtracted.
- ◆ Dry out did not occur, maximum heat transport capacity is unknown. Theoretical capacity is 600 watts.



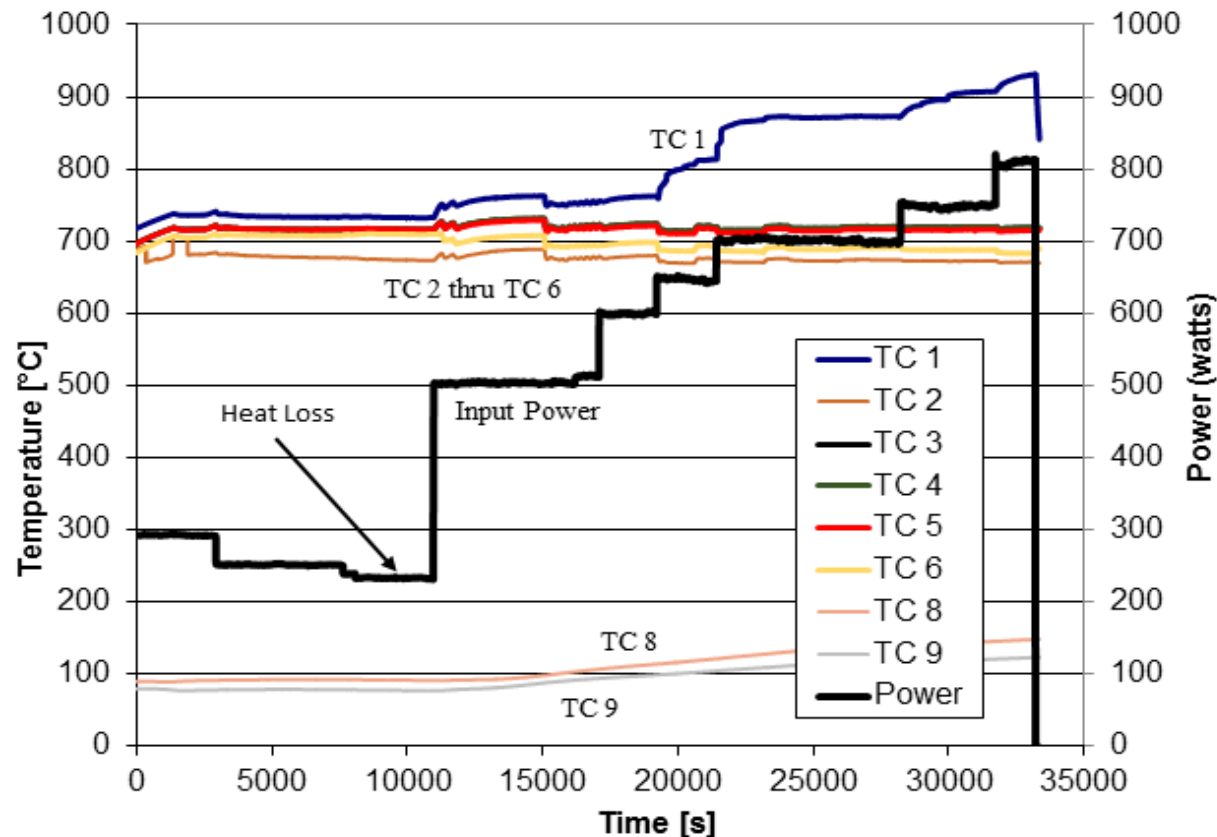
Thermosyphon testing of straight arterial heat pipe in vacuum chamber





## One Bend

- ◆ Elevation 0.3" against gravity was introduced to avoid puddle flow (considered horizontal position).
- ◆ The final power input into the system was 750W yielding a transport power of 520W when the heat losses (230 watts measured for this configuration) are subtracted.



Horizontal testing of one bend arterial heat pipe in vacuum chamber

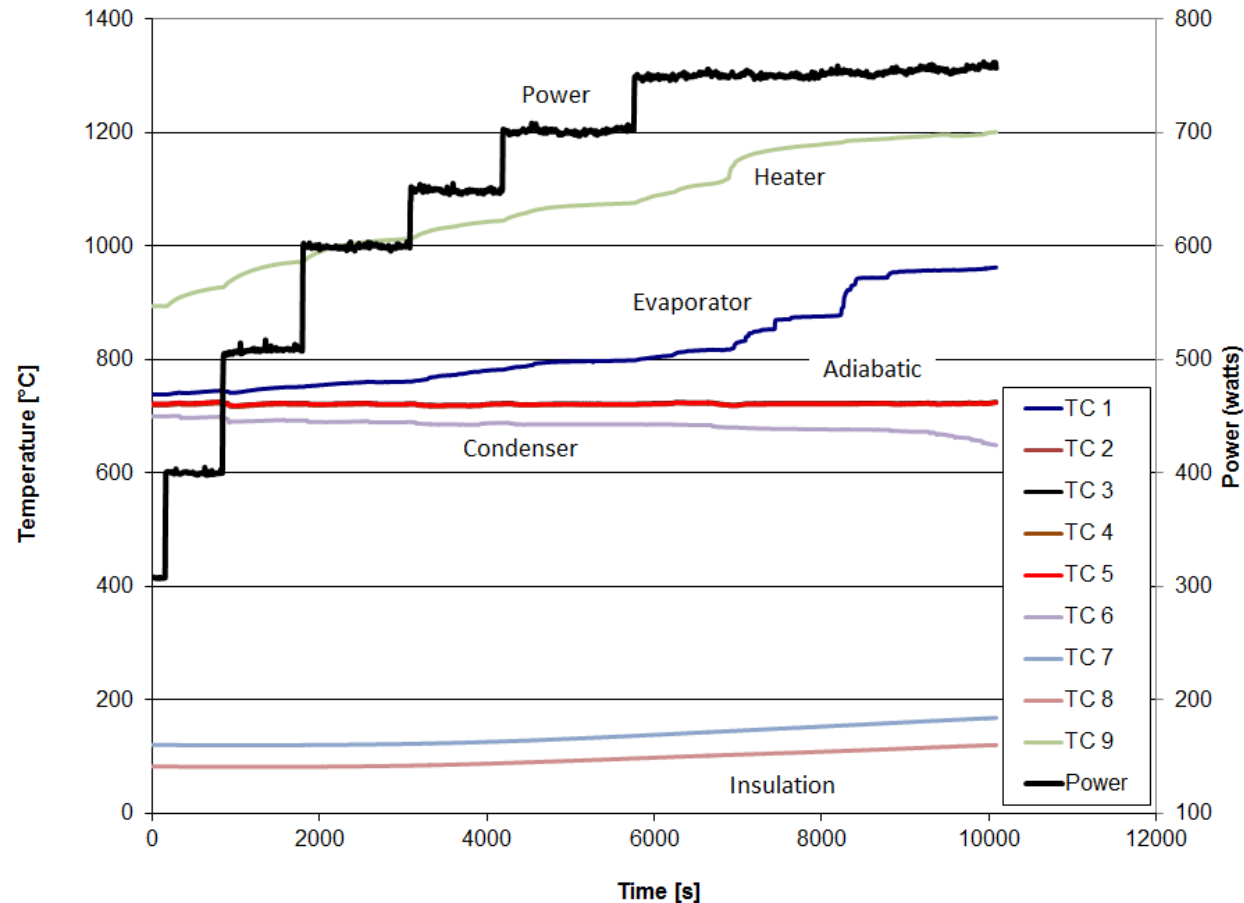






## Two Bends

- ◆ Elevation 0.3" against gravity was introduced to avoid puddle flow (considered horizontal position).
- ◆ The final power input into the system was 750W yielding a transport power of 443W when the heat losses (307 watts measured for this configuration) are subtracted.



Horizontal testing of two bend arterial heat pipe in vacuum chamber







## Radius Bend Artery Heat Pipe - Summary

- ◆ Table summarizes power transport capacity for radius bend heat pipes.
- ◆ All configurations indicate artery flow.
- ◆ One bend power transport is almost the same as straight.
- ◆ Two bend power capacity is lower, but input power steps in testing was 50 watts, within test accuracy. It is possible that the multiple bends can begin to infringe on vapor flow, reducing power capacity. More data is required, will compile from thermosyphon testing.
- ◆ Heat pipe restarted (self-primed) after each dryout.

		Power (W)	
Configuration	Adverse Elevation	Theoretical	Measured
Straight	Horizontal (0.3")	706	520
	1"	472	340
One Bend	Horizontal		520
Two Bends	Horizontal		443

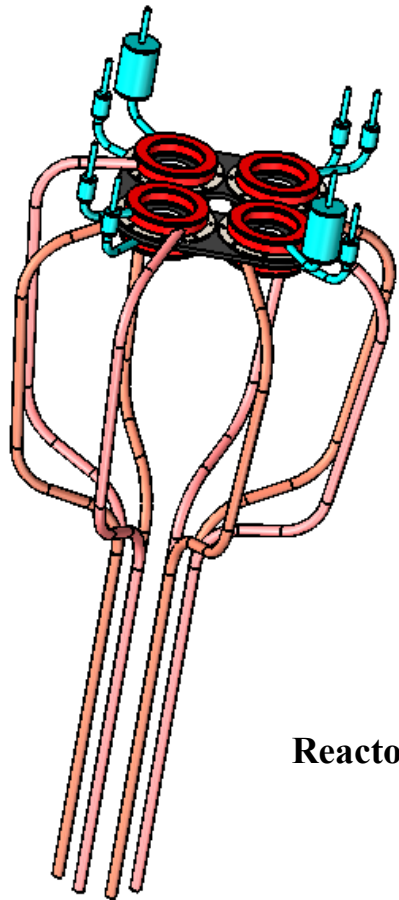
**Horizontal testing of one bend arterial heat pipe in vacuum chamber**





# System Configuration

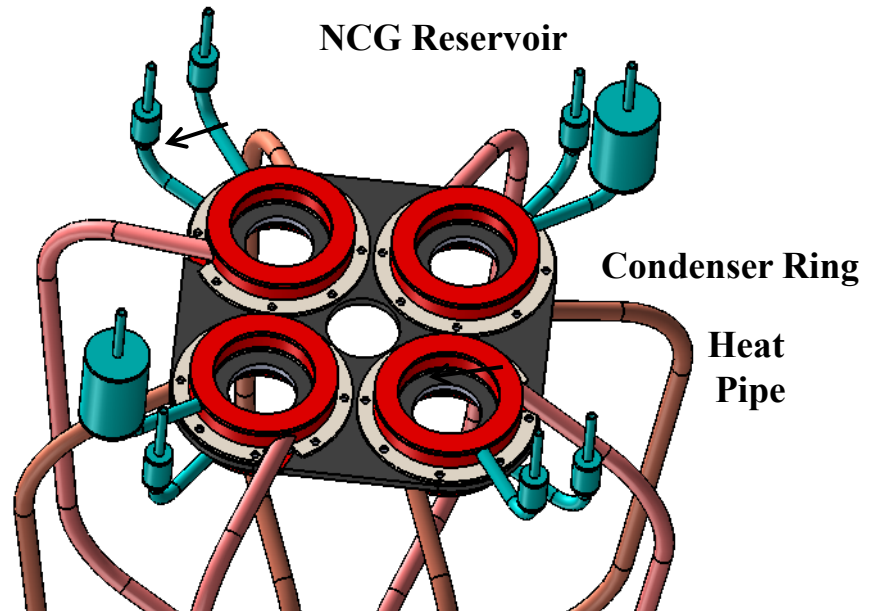
- The current design of the system determines the shape of the pipes



**Stirling Heater Head  
Cold Plate**

**Thermosyphon Kilopower  
Assembly**

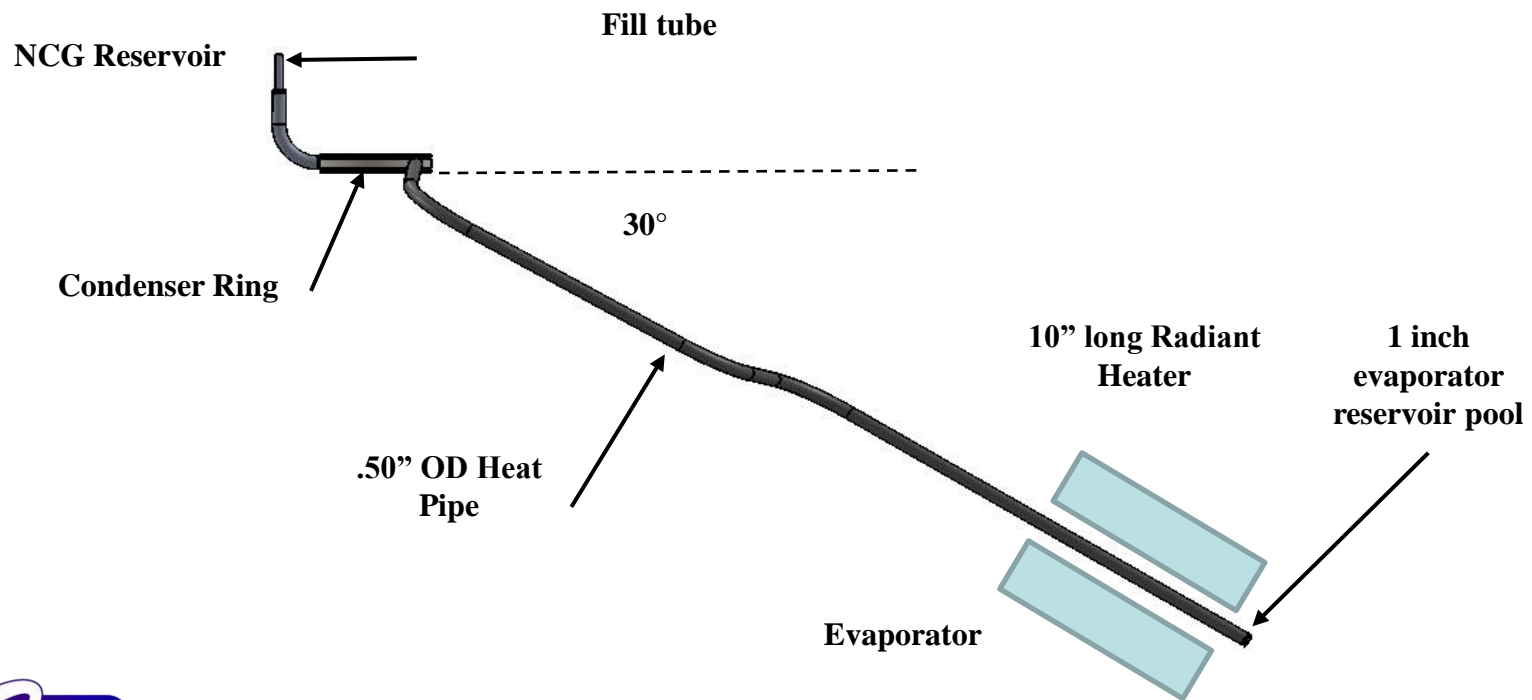
**Reactor side**





# Configuration for Vacuum Chamber Testing at ACT

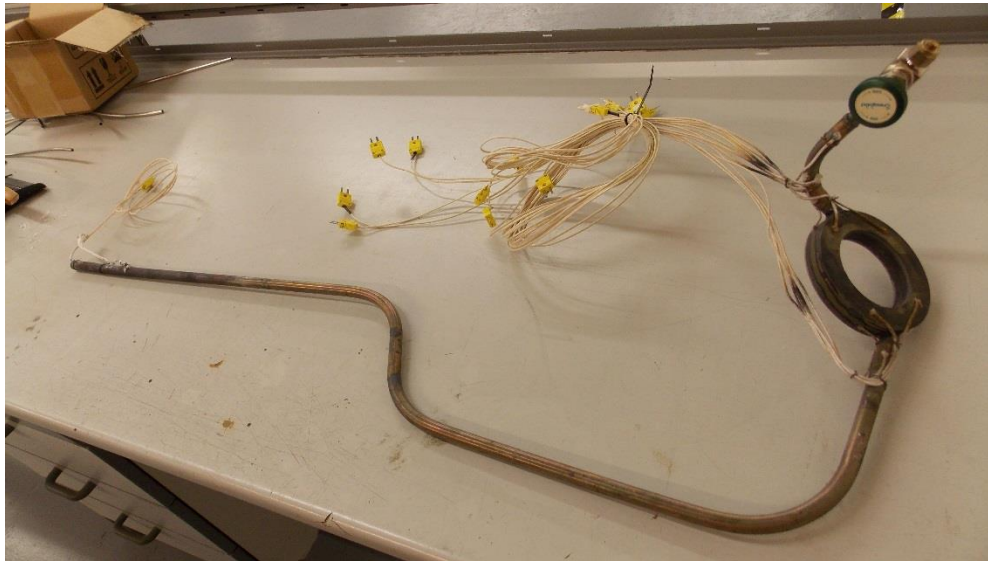
- Full scale length and shape. Condenser however at different angle.
- Inclination was  $30^\circ$  to fit in ACT vacuum chamber.
- NCG reservoir is present on condenser ring to evaluate if the use of an inert NCG gas will speed up startup time. The reservoir volume is  $0.50 \text{ in}^3$ .
- Thermosyphon to be performance tested without NCG. Argon NCG will be added to determine if any benefit to startup time and to shutdown configuration 2 thermosyphon.
- Operating temperatures:  $720^\circ\text{C}$ ,  $750^\circ\text{C}$ ,  $780^\circ\text{C}$ ,  $810^\circ\text{C}$ .





# Configuration for Vacuum Chamber Testing at ACT

- Initial evaluation and venting of NCG in ambient air.
- Initial heat up and burping indicated NCG tends to settle in the region on the sharp interface side of the heat pipe connection, likely driven there (past the NCG reservoir) by the momentum of the incoming vapor being around the condenser ring. This NCG does eventually settle into the NCG reservoir. Design improvement will have the heat pipe come in perpendicular to the condenser ring side. This will direct vapor around both sides of the condenser ring into the NCG reservoir.



**Fabricated Configuration 1 Thermosyphon**



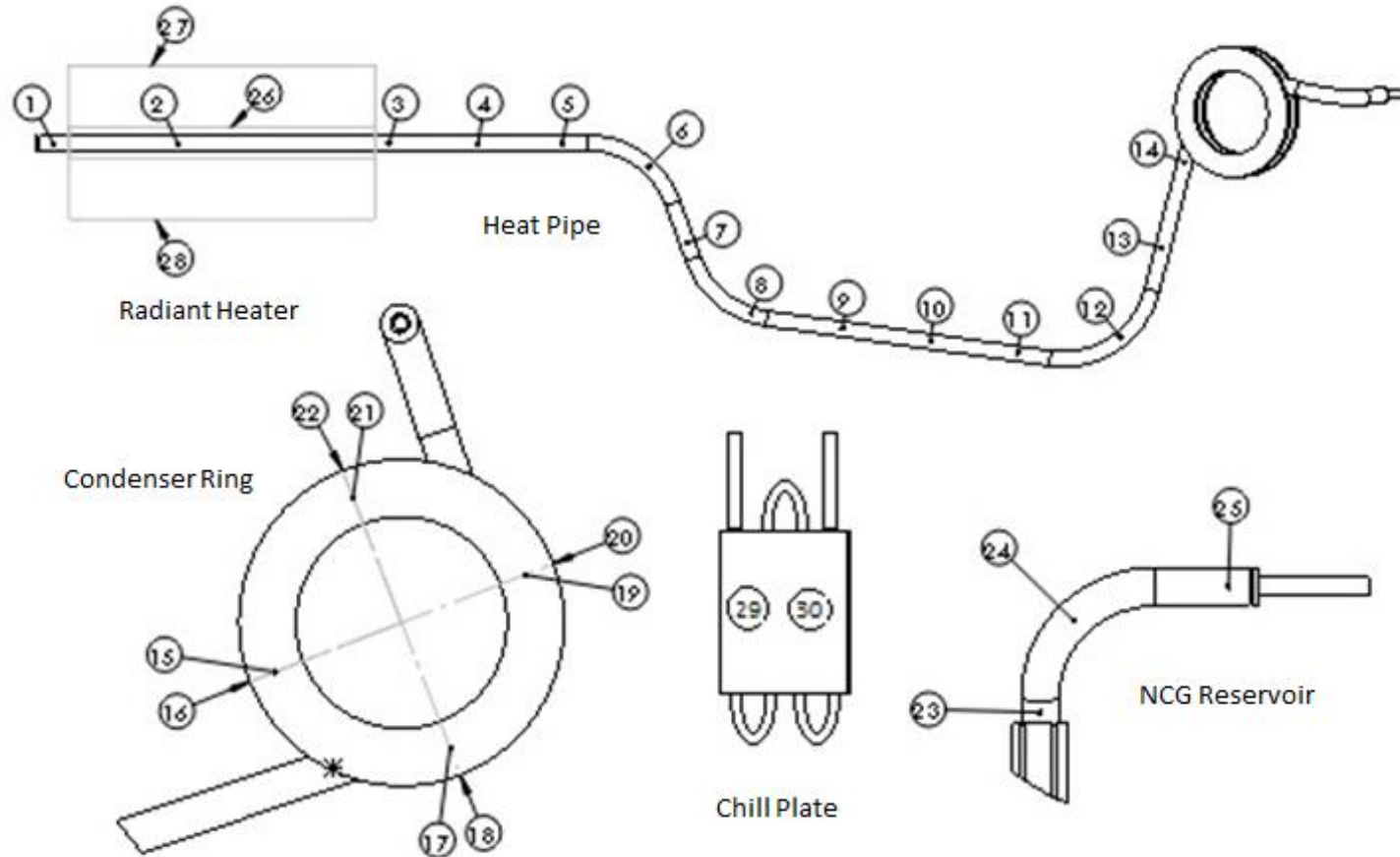
**Condenser ring bottom. Dark area is settled NCG**





# Configuration for Vacuum Chamber Testing at ACT

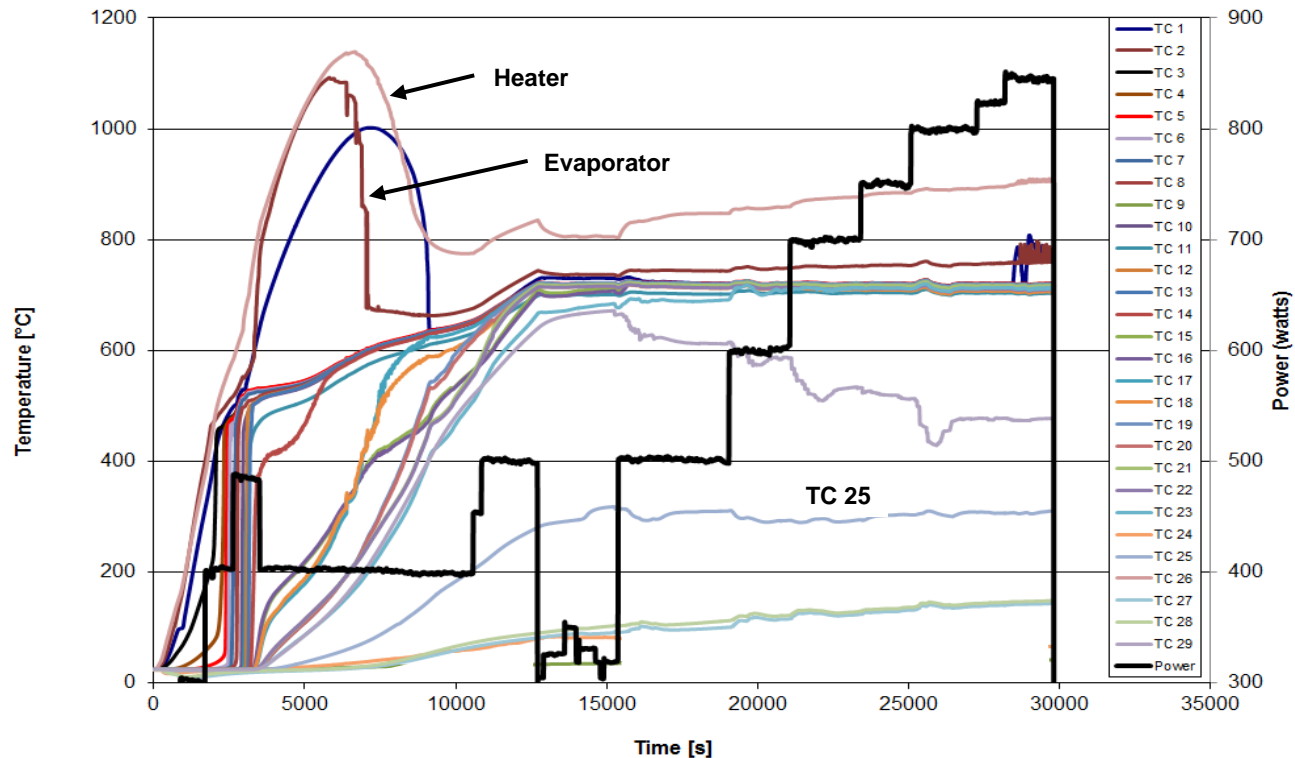
## ◆ Location and Numbering of Thermocouples.





## Performance Testing at 720°C

- ◆ Thermosyphon operation, inclination 30°, 23 inches gravity aided.
- ◆ The maximum input power before dryout is 820 watts. With a heat loss of 300 watts, this gives a net power carrying capacity of ~ 520 watts.



**Power capacity testing thermosyphon, 720°C. Screen wick in evaporator only.**

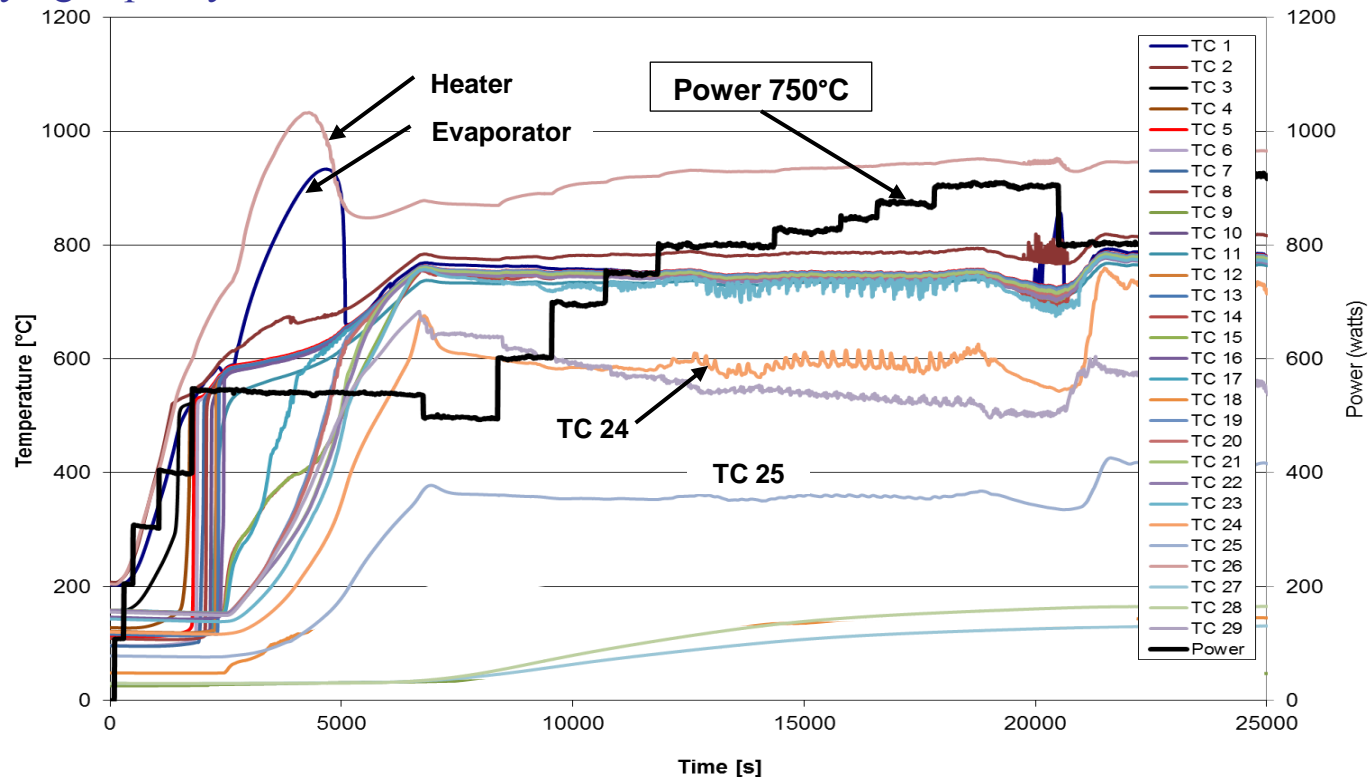






## Performance Testing at 750°C

- ◆ Thermosyphon operation, inclination 30°, 23 inches gravity aided.
- ◆ The maximum input power before dryout is 875 watts. With a heat loss of 380 watts, this gives a net power carrying capacity of 495 watts.



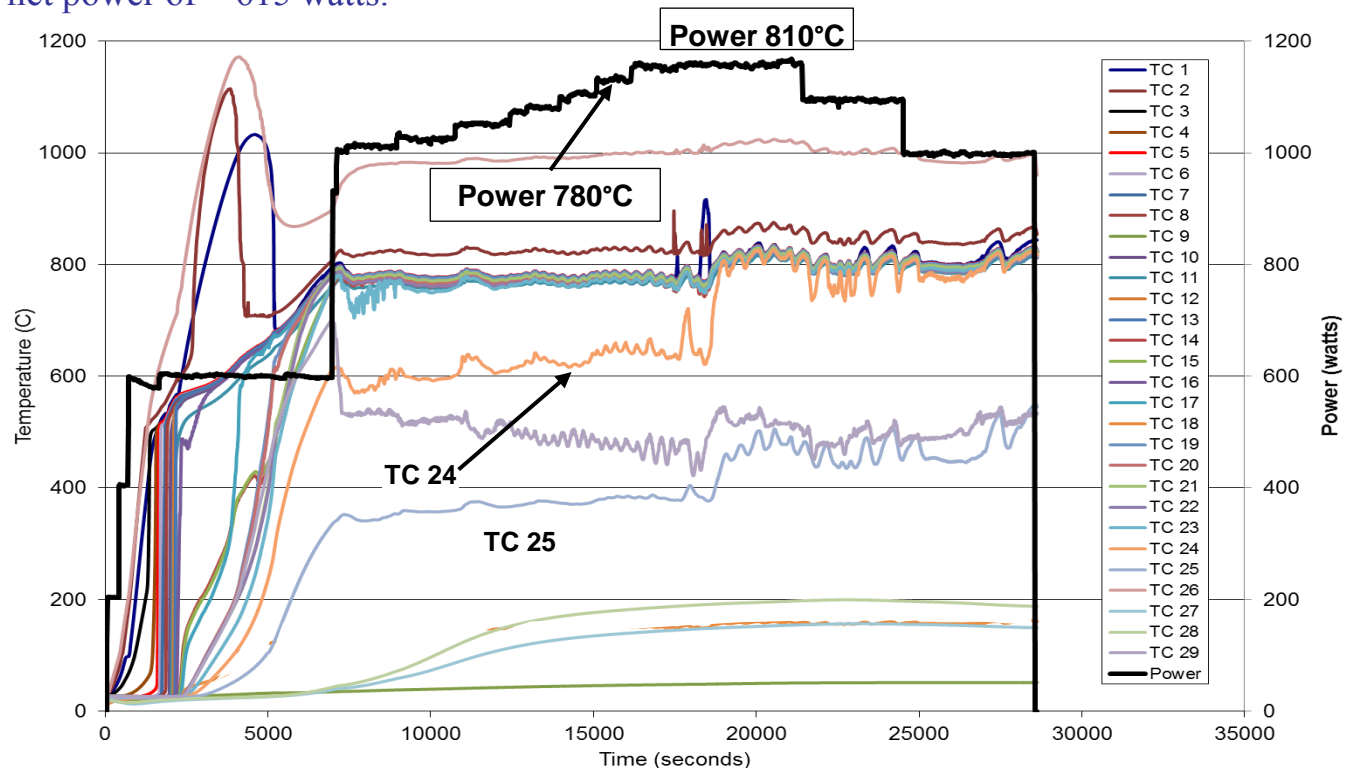
**Power capacity testing thermosyphon, 750°C. Screen wick in evaporator only.**





## Performance Testing at 780°C and 810°C

- ◆ Thermosyphon operation, inclination 30°, 23 inches gravity aided.
- ◆ The maximum input power at 780°C before dryout is 1130 watts. With a heat loss of 440 watts, this gives a net power carrying capacity of ~ 690 watts.
- ◆ The maximum input power at 810°C is 1155 watts. No dryout, this was the capacity of the heaters. With a heat loss of 540 watts, this gives a net power of ~ 615 watts.



**Power capacity testing thermosyphon, 780°C and 810°C. Screen wick in evaporator only.**







# Performance Testing at ACT - Summary

- ◆ Table summarizes power transport capacity for the configuration 1 thermosyphon.
- ◆ Increasing the operating temperature increases the power carrying capacity. This is do to better sodium heat transfer properties at the higher temperatures.
- ◆ Thermosyphon restarted after each dryout.

Configuration	Temperature {C}	Elevation (in)	Total Power (W)	Heat Loss (W)	Transported Power (W)	Theoretical Power (W) (flooding)
Thermosyphon - Screen in the Evaporator Only	720	23	820	300	520	678
	750	23	875	380	495	718
	780	23	1130	440	690	777
	810	23	1155*	540	615*	836

\* No dryout - reached the temperature limit of radiant heater

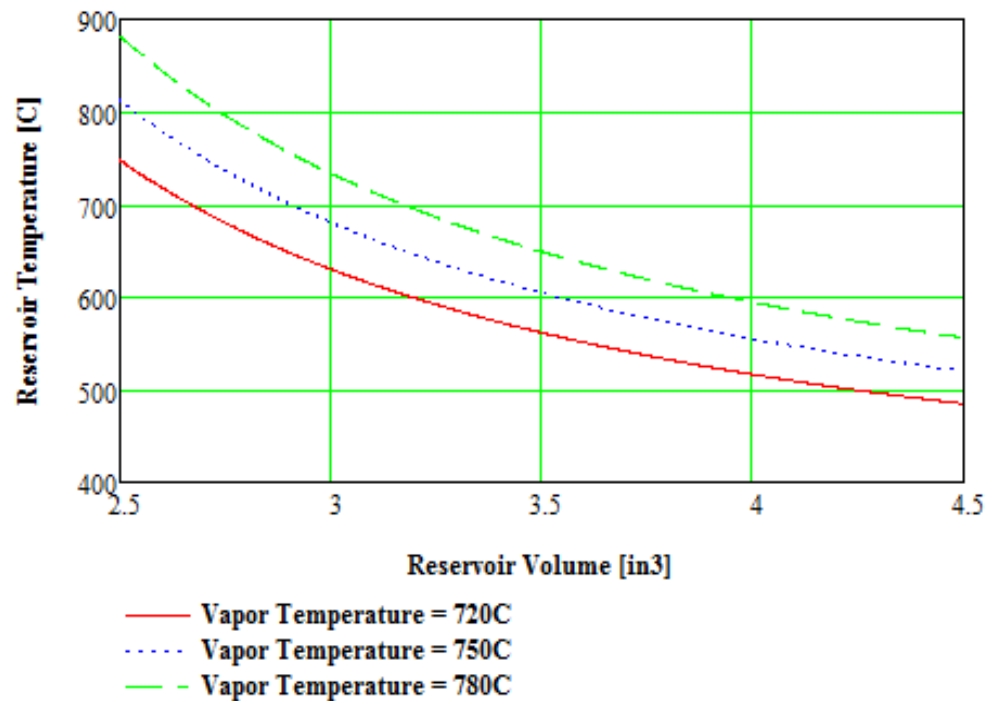
**Horizontal testing of one bend arterial heat pipe in vacuum chamber**





# VCHP Feature

- ◆ Non Condensable Gas reservoir sizing to allow shut down of thermosyphon during operation.
- ◆ For each shut down, the vapor/NCG front is located at the exit of the evaporator.
- ◆ The volume of the donut shaped condenser ring is 3.01 in<sup>3</sup> and the length of the adiabatic section is 36 in.
- ◆ As seen in the figure the feasibility of having a front location at the bottom of the adiabatic section is high. *For example*, for a 720°C operating pipe, to shut down the entire pipe, a 3in<sup>3</sup> reservoir must be heated to 630°C, while a 4in<sup>3</sup> reservoir must be heated only to 515°C.
- ◆ The final NCG reservoir shape is 4in<sup>3</sup> and it was determined that the required volumes will be manageable in the final Kilopower installation.





# Condenser Development

- 24 inch heat pipe/thermosyphon assembly to test new concepts before building a full size heat pipes. Arterial to screen heat pipe at the condenser.
- Sodium charge into the artery at the evaporator end.
- Condenser wick connected to the heat pipe artery with multiple screen wraps.
- Fully fabricated, charged, currently testing



**Condenser Ring (during construction)**

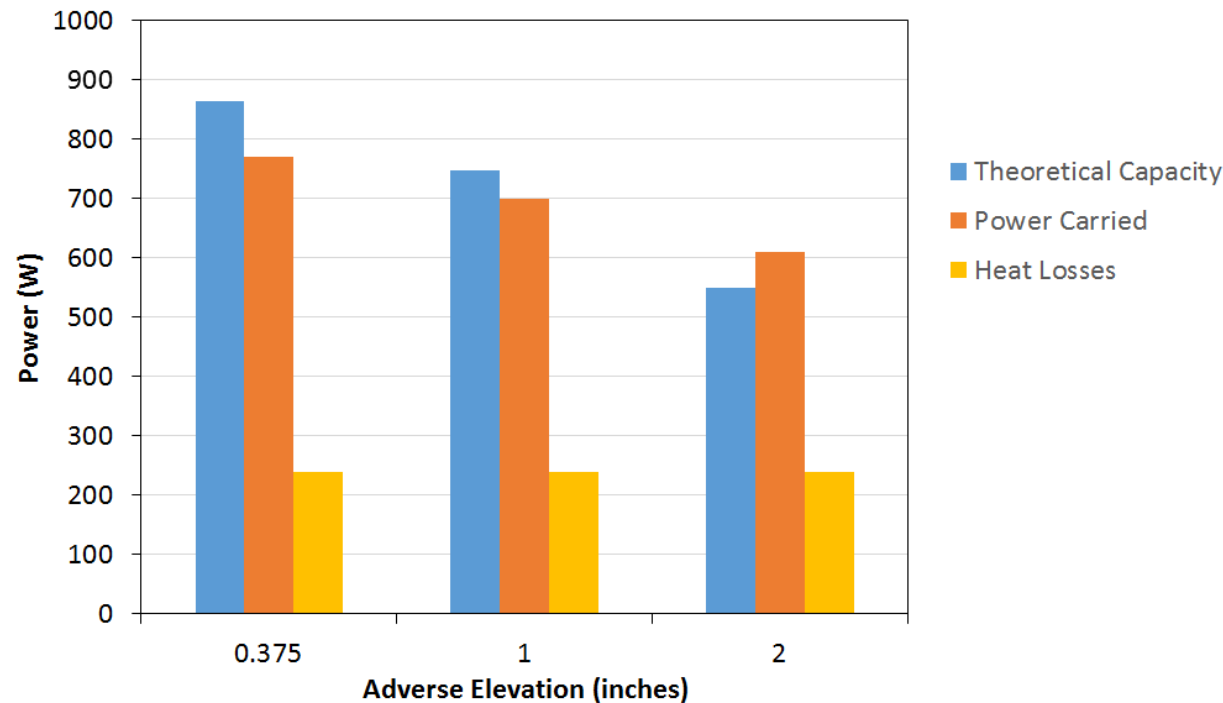




# 24" Heat Pipe Performance in Vacuum Chamber, Test Summary

- Performance summary for hybrid screen/artery heat pipe with venting pores at 720°C

- ◆ Pipe performs reasonably well
- ◆ Hybrid wick performance is validated
  - ▶ Deliverable will have a hybrid wick
- ◆ Gravity aided performance ~ 840W



	Adverse Elevation		
	0.375"	1"	2"
Measured Power (W)	1010	940	850
Heat Loss (W)	240	240	240
Transported Power (W)	770	700	610
Theoretical Power Artery W/Vent Pores (W)	864	747	550





# Acknowledgements

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  - Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration
- Mr. Marc Gibson was the NASA GRC contract technical monitor
- Tim Wagner, Larry Waltman and Corey Wagner were the laboratory technicians responsible for the development of the self-venting arterial heat pipe





# Questions



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